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Photonuclear Benchmarks with a Comparison of COG and MCNPX Results

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Disclaimer

The IAEA Photonuclear Data Library

The Nuclear Data Section of the International Atomic Energy Agency (IAEA) has distributed an evaluated photonuclear data library [**1**] in standard ENDF-6 format that is intended for use in transport codes. This "IAEA Photonuclear Data Library" consists of a number of individual ASCII text files for various elements that have been recently processed into the single binary (COG data library) file "COGPNUC" with corresponding changes to the COG code for use in transport calculations involving photonuclear reactions [**2**].

Barber and George Benchmark Experiments

Barber and George [**3**] have measured the total neutron yields produced by the bombardment of thick targets of C, Al, Cu, Ta, Pb, and U by mono-energetic beams of electrons. They estimated the absolute accuracy of their experimental measurements to be ±15%.

COG Benchmark Model Details

Barber and George reported the target thicknesses as areal densities (in g/cm^2). The thicknesses (in cm) are calculated for each target using the reported areal density and the assumed density as given in Table 1.

Table 1. Reported and Calculated Target Thicknesses

Target	Density	Thickness	
C-I	$1.70 g/cm^3$	$38.91 g/cm^2$	22.8882 cm
Al-I	$2.70 g/cm^3$	$24.19 g/cm^2$	8.9593 cm
Cu-A	$8.92 g/cm^3$	$1.372 g/cm^2$	0.1538 cm
Cu-I	$8.92 g/cm^3$	$13.26 g/cm^2$	1.4866 cm
Cu-II	$8.92 g/cm^3$	$26.56 g/cm^2$	2.9776 cm
Cu-III	$8.92 g/cm^3$	$39.86 g/cm^2$	4.4686 cm
Cu-IV	$8.92 g/cm^3$	$53.13 g/cm^2$	5.9563 cm
Ta-1	$16.6 g/cm^3$	$6.21 g/cm^2$	0.3741 cm
Pb-I	$11.34 g/cm^3$	$5.88 g/cm^2$	0.5185 cm
Pb-II	$11.34 g/cm^3$	$11.42 g/cm^2$	1.0071 cm
Pb-III	$11.34 g/cm^3$	$17.30 g/cm^2$	1.5256 cm
Pb-IV	$11.34 g/cm^3$	$22.89 g/cm^2$	2.0185 cm
Pb-VI	$11.34 g/cm^3$	$34.42 g/cm^2$	3.0353 cm
U-I	$18.95 g/cm^3$	$6.17 g/cm^2$	0.3256 cm
U-II	$18.95 g/cm^3$	$12.42 g/cm^2$	0.6554 cm
U-III	$18.95 g/cm^3$	$18.61 g/cm^2$	0.9821 cm

Each target is modeled as a 4.5"x4.5" parallelepipedon with the thickness given in Table 1. The source is specified as a mono-energetic electron beam distributed uniformly throughout a 0.5"-diameter disc centered on one of the 4.5" x 4.5" faces of the parallelepipedon and directed inward perpendicularly to the plane of the surface. A vacuum boundary condition is applied to the surface of the parallelepipedon and thus particle transport only takes place in one medium.

Coupled electron, photon and neutron transport COG [**4**] calculations were performed using version 10.171 on the GPS machines. To enable photonuclear reactions the user must specify "basic electron photon neutron photonuclear" in the COG "basic block" of each input file. The numbers of neutrons (and other particles) that escape the target were counted by specifying a "boundary-crossing detector" with "particle counting" on the surface of the parallelepipedon. A sample COG input listing is provided in Appendix A.

Results of Benchmark Calculations

Table 2 lists the target, the energy of the electron beam and the experimentally measured [**3**], [**5**] and calculated neutron yield per million incident electrons. The MCNPX calculational results were run to high precision and are those reported recently by researchers at Los Alamos [**5**]. The COG results are those of the authors and are based on simulations of one million electron histories for electrons above 1.0 MeV. The results are also provided in graphical form in Appendix B.

Table 2. Experimental and Calculated Neutron Yields from Electron Bombardment

Material Target	Electron Beam Energy	Neutron Yield per 10^6 Electrons		
		Experiment	**MCNPX**	**COG**
C-I	26.0 MeV	31±5	20	27±1
	28.3 MeV	60±9	45	54±2
	34.4 MeV	173±26	140	155±3
Al-I	22.2 MeV	46±7	35	37±1
	28.3 MeV	210±32	158	162±1
	34.3 MeV	430±65	329	332±2
Cu-A	13.9 MeV	1.1±0.2	0.6	0.8±0.1
	16.3 MeV	3.6±0.5	2.8	3.1±0.2
	19.9 MeV	11.8±1.8	8.6	9.1±0.5
	23.5 MeV	21.1±3.2	14.0	15.9±0.6
	25.9 MeV	26.3±3.9	17.2	18.4±0.7
	28.2 MeV	30.9±4.6	19.7	20.0±0.7
	31.9 MeV	35.8±5.4	22.6	24.2±0.7
Cu-I	16.1 MeV	30±5	39	44±1
	21.2 MeV	260±39	260	279±3
	28.3 MeV	820±123	739	772±4
	34.4 MeV	1290±194	1128	1166±5
	35.5 MeV	1390±209	1189	1245±5

Table2.ExperimentalandCalculatedNeutronYieldsfromElectronBombardment(cont.)

Cu-II	16.1MeV	50±8	66	73±1
	21.2MeV	430±65	446	483±3
	28.3MeV	1390±209	1325	1387±6
	34.4MeV	2370±356	2117	2221±7
Cu-III	16.1MeV	70±11	83	94±1
	21.2MeV	530±80	562	602±4
	28.3MeV	1800±270	1688	1784±6
	34.4MeV	2930±440	2729	2873±8
Cu-IV	16.1MeV	100±15	94	105±1
	21.2MeV	600±90	634	677±4
	28.3MeV	2130±320	1910	1989±7
	34.4MeV	3350±503	3104	3241±8
Ta-I	10.3MeV	80±12	8.2	7.5±0.2
	18.7MeV	520±78	578	544±5
	28.3MeV	1380±207	1433	1362± 7
	34.3MeV	1810±272	1726	1655±8
Pb-I	18.7MeV	730±110	627	569±3
	28.3MeV	1690±254	1366	1298±5
	34.5MeV	2120±318	1611	1536±5
Pb-II	18.7MeV	1320±198	1135	1051±5
	28.3MeV	3450±518	2871	2731±7
	34.5MeV	4720±708	3717	3575±8
Pb-III	18.7MeV	1770±266	1503	1395±5
	28.3MeV	4690±704	3953	3792±8
	34.5MeV	6460±969	5264	5099±9
Pb-IV	18.7MeV	2100±317	1748	1645±6
	28.3MeV	5370±806	4668	4506±9
	34.5MeV	7770±1166	6290	6114±10
Pb-VI	18.7MeV	2500±375	2053	1933±6
	28.3MeV	6670±1000	5556	5381±9
	34.5MeV	9000±1350	7575	7387±10
U-I	16.4MeV	1070±161	N/A	1029±7
	21.1MeV	2330±350	N/A	2161±10
	28.4MeV	3860±579	N/A	3268±12
	35.5MeV	4880±732	NA	3802±14
U-II	16.4MeV	1950±293	N/A	1907±9
	21.1MeV	4310±647	N/A	4229±14
	28.4MeV	7850±1178	N/A	7143±18
	35.5MeV	10735±1610	N/A	9229±21

Table 2. Experimental and Calculated Neutron Yields from Electron Bombardment (cont.)

U-III	11.5 MeV	380±57	N/A	326±3
	16.4 MeV	2530±380	N/A	2536±11
	21.1 MeV	5900±885	N/A	5676±17
	28.4 MeV	10460±1569	N/A	9814±22
	35.5 MeV	14940±2241	N/A	13175±25

Detailed Remarks

Graphite: The COG results are very good agreement with the measurements of Barber and George for graphite. Note that MCNPX under-predicts the neutron yield slightly for these measurements. Aluminum: COG and MCNPX results are good agreement with each other but both codes under-predict the neutron yield by nearly 25%. Copper: COG and MCNPX are in good agreement with each other but both codes under-predict the neutron yields of the thinnest target (Cu-A) by as much as 35%. Tantalum: COG and MCNPX are in excellent agreement with measurement for incident electron energies above 18 MeV. However, both codes under-predict the neutron yield at low energy by an order of magnitude. Lead: COG and MCNPX are in good agreement with each other but both codes under-predict the neutron yields of the thinnest targets (Pb-I and Pb-II) by as much as 30%. Uranium: COG results are in good agreement with measurement.

Conclusion

COG (and MCNPX) calculated neutron yields are generally in good agreement with the measurements of Barber and George with no over-predicted yields but users are cautioned that calculated yields may be under-predicted by as much as 35% (see Cu-A) or by an order-of-magnitude at very low energies near the reaction threshold (see Ta-I). Nonetheless, these results validate COG for use with the IAEA Photonuclear Data Library (COGPNUC) as another state-of-the-art computational method (such as MCNPX) for simulating neutron production in C, Al, Cu, Ta, Pb, and U due to photonuclear reactions.

References

[**1**]   P. Oblozinsky et al., "Handbook on photonuclear data for applications, Cross sections and Spectra", IAEA-TECDOC Draft No 3, March 2000.

[**2**]   Edward M. Lent, personal communication.

[**3**]   W. C. Barber and W. D. George, "Neutron Yields from Targets Bombarded by Electrons", *Physical Review*: 116(6) 1551–1559, December 15, 1959.

[**4**]   Richard M. Buck, Edward M. Lent, Tom Wilcox and Stella Hadjimarkos, "COG User's Manual, A Multiparticle Monte Carlo Transport Code", Fifth Edition.

[**5**]   M. C. White, R. C. Little, M. B. Chadwick, P. G. Young, and R. E. MacFarla   ne, "PhotonuclearPhysicsinRadiationTransport   –II:Implementation", *NuclearScienceand Engineering*:144,174   –189(2003).

Acknowledgements

AppendixA

SampleCOGInputListing

```
16.4 MeV electrons on the U-I Target
$ ----------------------------------------------------------------------------
$ Physical Review: 116(6)1551-1559(1959), "Neutron Yields from Targets Bombarded
$ by Electrons", W. C. Barber and W. D. George (Stanford University).
$
$ Nuclear Science and Engineering: 144,174-189(2003), "Photonuclear Physics in
$ Radiation Transport - II: Implementation", M. C. White, R. C. Little, M. B.
$ Chadwick, P. G. Young and R. E. MacFarlane (LANL).
$ ----------------------------------------------------------------------------
basic
  electron photon neutron photonuclear
source
  npart=1E+6 nofile
  define position = 1 ss-disk -0.1628 0 0 0 0 0 0.635 $ 0.5" diameter beam spot
  define energy   = 1 electron line 16.4 1
  define time     = 1 steady
  define angle    = 1 1 0 0 fixed
  increment 1 position=1 energy=1 time=1 angle=1
mix nlib=ENDFB6R7
   mat=1 a-f 18.95 u234 0.005 u235 0.720 u238 0.99275
assign
  1 1 1 1.0  2 0 2 1.0
egs
  pegslib=/g/g12/u381872/runPEGS4/U.dat $ PEGS4 (U) library file on GPS
  esectors = 1
  ecut 1.0
geometry
  sector 1 U-I    -1
  sector 2 Void    1 -2
  boundary vacuum     2
surfaces
 1 box 0.3256 11.43 11.43 $ Thickness = (6.17 g/sq.cm)/(18.95 g/cc)
 2 box 0.4    12.   12.
detector
 number=#0000001 title="number of leakage neutrons per incident electron"
 boundary counts 1 2 276.176 $ = [4(0.3256) + 2(11.43)](11.43)
end
```
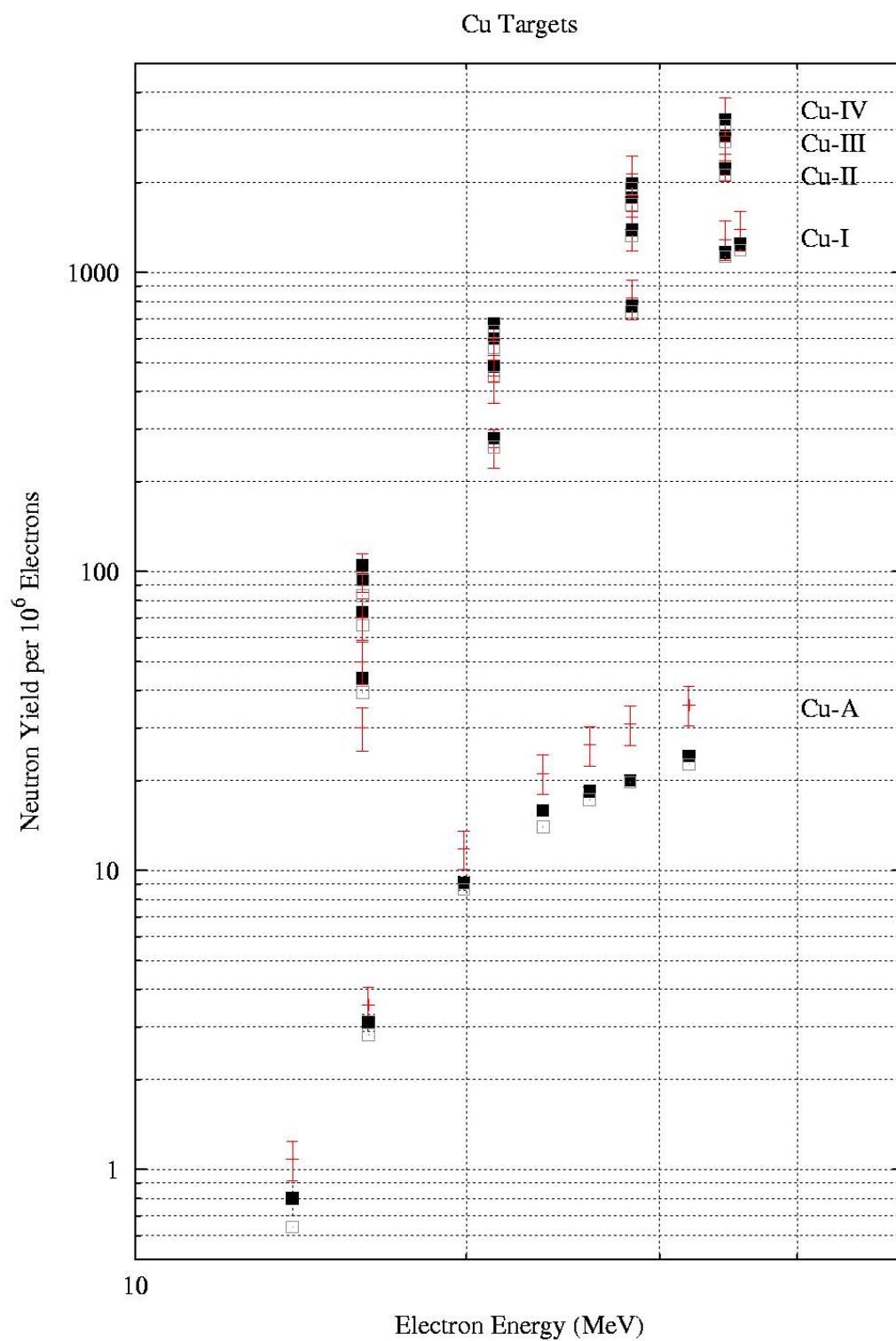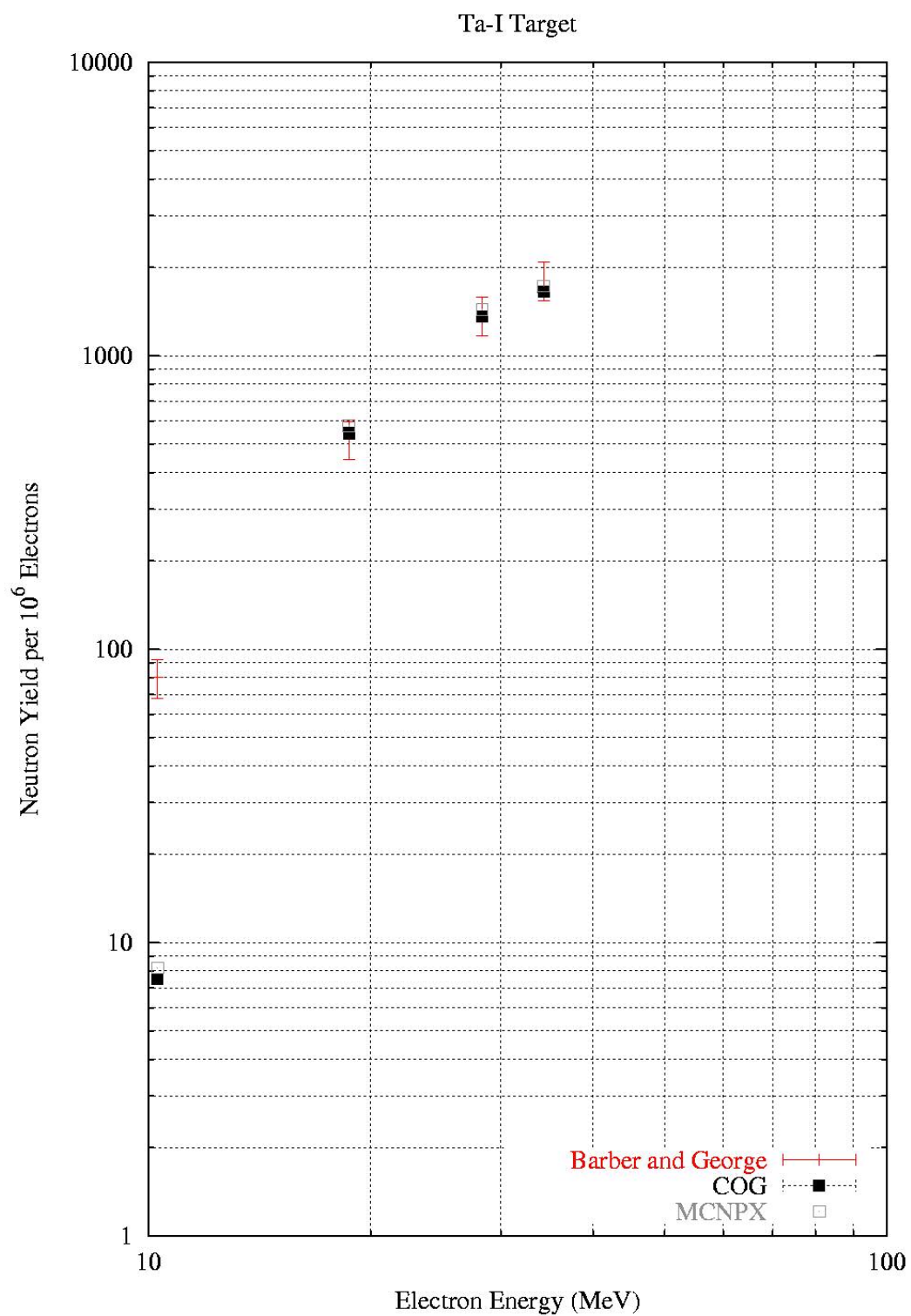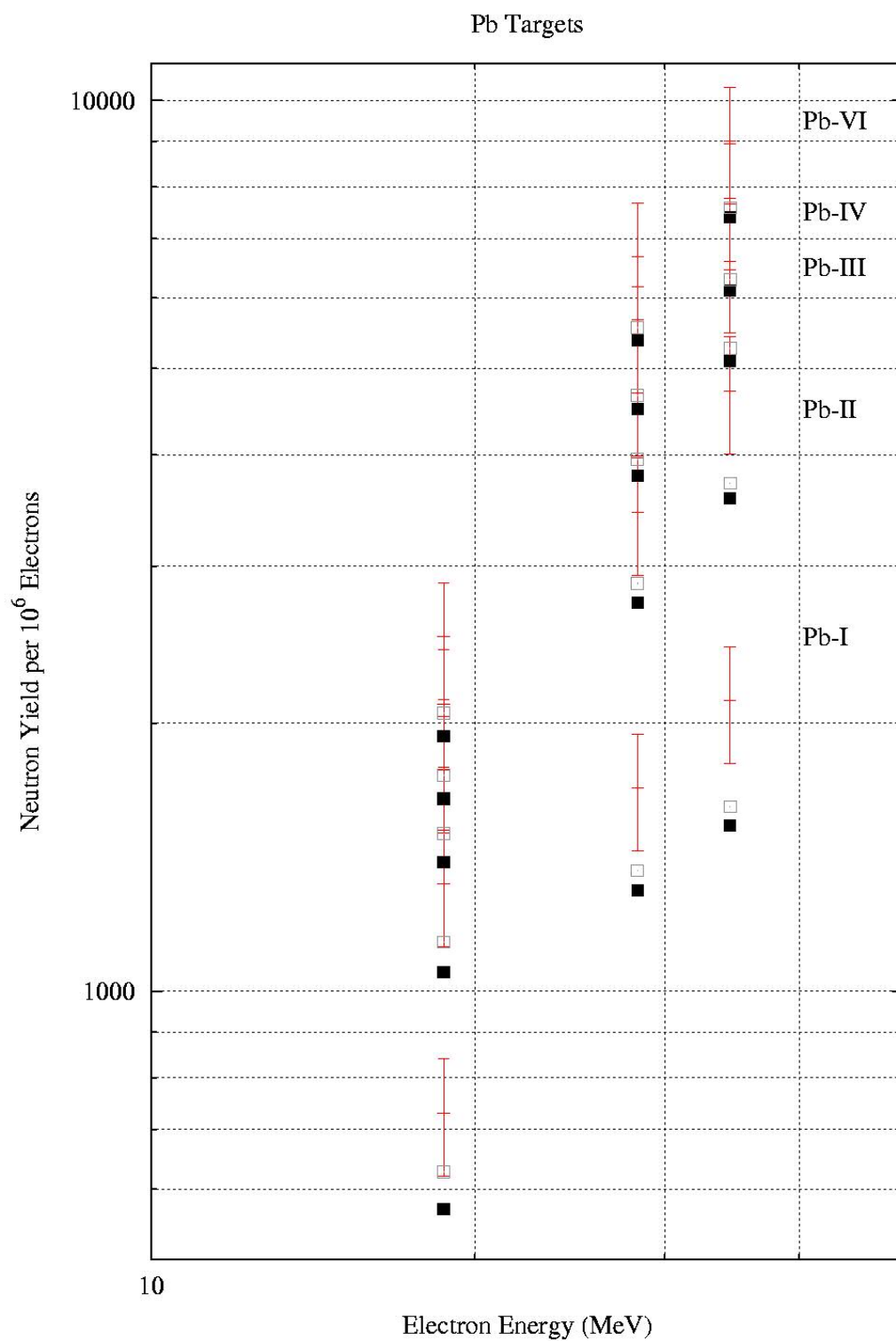
Appendix B

Graphs of the Results

C-I Target

Al-I Target

Cu Targets

Neutron Yield per 10^6 Electrons

Electron Energy (MeV)

Cu-IV
Cu-III
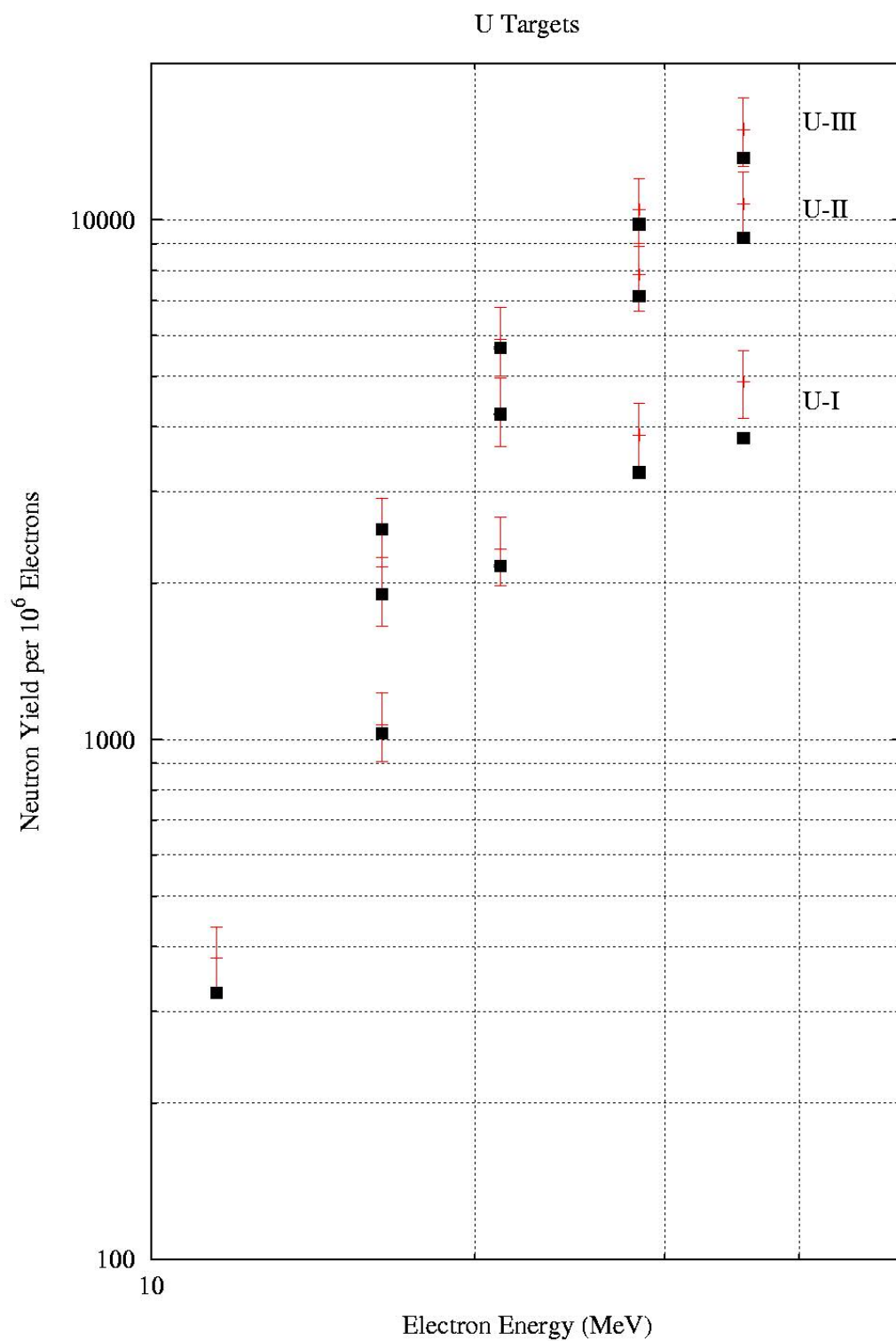Cu-II
Cu-I
Cu-A

Pb Targets

U Targets
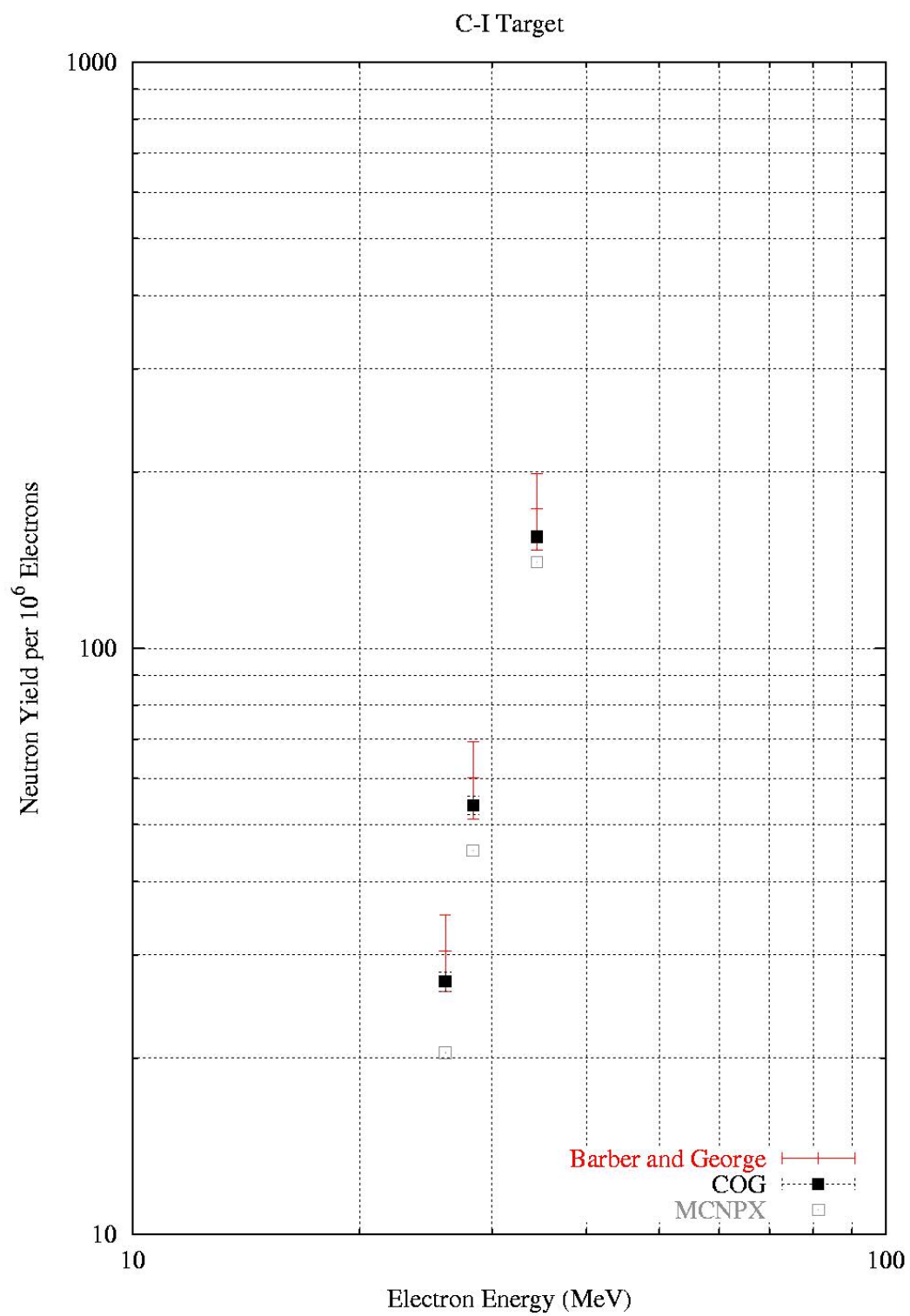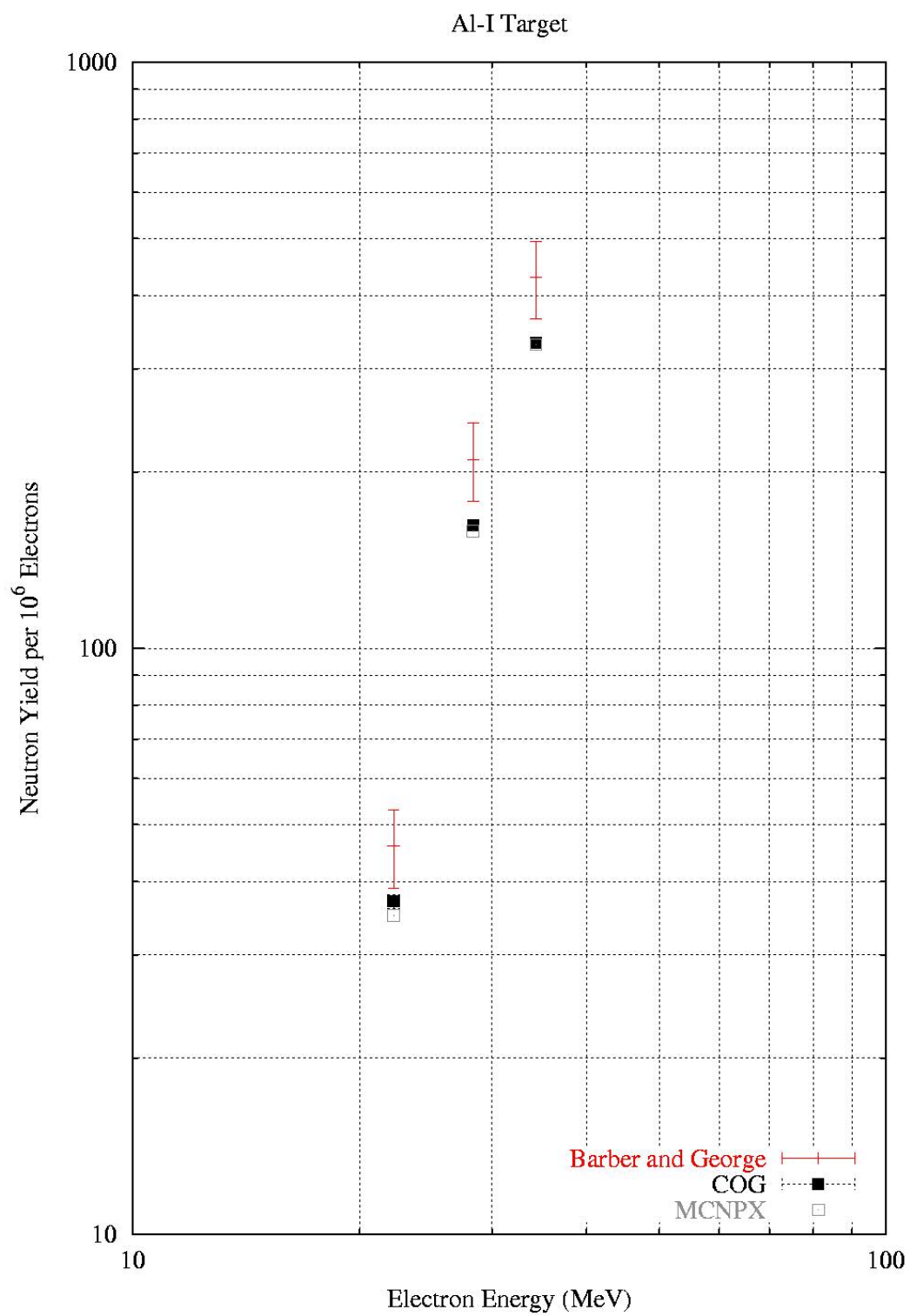
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